Initial Skill Acquisition of Handrim Wheelchair Propulsion

Vegter, Riemer J. K.; de Groot, Sonja; Lamoth, Claudine J.; Veeger, DirkJan (H. E. J.); van der Woude, Lucas H. V.

Published in:
IEEE Transactions on Neural Systems and Rehabilitation Engineering

DOI:
10.1109/TNSRE.2013.2280301

Publication date:
2014

Initial Skill Acquisition of Handrim Wheelchair Propulsion: A New Perspective

Riemer J. K. Vegter, Sonja de Groot, Claudine J Lamoth, Dirkjan Hej Veeger, and Lucas H. V. van der Woude

***Abstract*—To gain insight into cyclic motor learning processes, hand rim wheelchair propulsion is a suitable cyclic task, to be learned during early rehabilitation and novel to almost every individual. To propel in an energy efficient manner, wheelchair users must learn to control bimanually applied forces onto the rims, preserving both speed and direction of locomotion. The purpose of this study was to evaluate mechanical efficiency and propulsion technique during the initial stage of motor learning. Therefore, 70 naive able-bodied men received 12-min uninstructed wheelchair practice, consisting of three 4-min blocks separated by 2 min rest. Practice was performed on a motor-driven treadmill at a fixed belt speed and constant power output relative to body mass. Energy consumption and the kinetics of propulsion technique were continuously measured. Participants significantly increased their mechanical efficiency and changed their propulsion technique from a high frequency mode with a lot of negative work to a longer-slower movement pattern with less power losses. Furthermore a multi-level model showed propulsion technique to relate to mechanical efficiency. Finally improvers and non-improvers were identified. The non-improving group was already more efficient and had a better propulsion technique in the first block of practice (i.e., the fourth minute). These findings link propulsion technique to mechanical efficiency, support the importance of a correct propulsion technique for wheelchair users and show motor learning differences.**

***Index Terms*—Biomechanics, motor learning, rehabilitation, wheelchairs.**

I. Background

WHEN confronted with a new motor task the performance of this task will usually improve through practice. This process of skill acquisition is a key element of human functioning during daily life and is an essential element during rehabilitation after disease or injury. A typical example of a totally new motor skill to be learned during rehabilitation is handrim wheelchair propulsion. Despite advances in technology and possibilities of other propulsion mechanisms the hand rim-propelled wheelchair is still the most often used form of mobility for those who lost their walking ability [1]. However, compared to other forms of ambulation the mechanical efficiency, i.e., the ratio of external power output over internal power production, of hand rim propulsion is low, while at the same time overuse problems are common [2]–[6]. Increased proficiency of the wheelchair propulsion skill is implied to improve mobility and reduce risks of injury, where literature specifically advises to use long smooth strokes leading to a reduced frequency of movement [7].

To gain insight into motor learning processes of cyclic motor tasks, the study of hand rim wheelchair propulsion, as a form of ambulation in daily life and rehabilitation is very suitable, because it entails several unique features. First, the cyclic nature of steady-state wheelchair propulsion makes it possible to evaluate performance using energy consumption as a generic outcome measure of motor learning [8]. Second, during the push and recovery phase there are multiple degrees of freedom enabling the user to perform the task in different ways, allowing propulsion technique to change between the left and right wheel and over time within one side [9]. Finally wheelchair propulsion is a task that is new to persons who just lost their walking ability and to many able-bodied participants as well. Therefore, in the study of motor learning able-bodied participants can serve as a model to study the early acquisition of this skill, without being too heterogeneous as a group, because of for instance spinal cord lesion level or upper-body asymmetries and without being hindered by the recent trauma early in rehabilitation.

With regard to motor learning in every day cyclic tasks [10], Sparrow and Newell proposed a constraints-based framework of metabolic energy expenditure, motor coordination and control [11]. Central to their model is the suggestion that observed movement patterns emerge from the interaction between different (external, task, and internal) constraints, with metabolic energy being the currency of the interaction. In other words, motor learning is the process of acquiring a movement pattern that minimizes the energy expenditure within the constraints of the task. In line with this model, several learning studies using different cyclical upper- or lower-body tasks found a reduction in energy expenditure through practice [8], [12]. For instance learning studies using a ski-simulator or a rowing-ergometer showed a reduction of energy expenditure through practice

Manuscript received March 06, 2013; revised May 23, 2013; accepted August 21, 2013. Date of publication October 09, 2013; date of current version January 06, 2014. The Open Access publication of this paper was funded by the Netherlands Organization for Scientific Research (NWO).

R. J. Vegter and C. J. Lamoth and are with the Center for Human Movement Sciences, University Medical Center Groningen, University of Groningen, 9712 CP Groningen, The Netherlands (e-mail: r.j.k.vegter@umcg.nl; c.j.c.lamoth@umcg.nl).

S. de Groot is with the Center for Human Movement Sciences, University Medical Center Groningen, University of Groningen, 9712 CP Groningen, The Netherlands, and also with the Amsterdam Rehabilitation Research Center—Reade, 1040 HG Amsterdam, The Netherlands (e-mail: s.d.groot@reade.nl).

D. H. Veeger is with the Faculty of Human Movement Sciences, Research Institute MOVE, Vrije Universiteit, 1081 BT Amsterdam, The Netherlands, and also with the Faculty of Mechanical, Maritime and Materials Engineering, Section Biomechatronics and Biorobotics, Delft University of Technology, 2628 CD Delft, The Netherlands (e-mail: h.e.j.veeger@vu.nl).

L. H. V. van der Woude is with the Center for Human Movement Sciences, University Medical Center Groningen, University of Groningen, 9712 CP Groningen, The Netherlands, and also with the Center for Rehabilitation, University Medical Center Groningen, University of Groningen, 9712 CP Groningen, The Netherlands (e-mail: l.h.v.van.der.woude@umcg.nl) .

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TNSRE.2013.2280301

while maintaining the same power output [8], [12]. The reduced energy cost in these different cyclical tasks coincided with an increase in movement amplitude and a decrease of movement frequency described as a longer-slower movement pattern. For handrim wheelchair propulsion this corresponds with a longer stroke, both in time and space when pushing and thus with a reduction in the frequency of these pushes.

Indeed motor learning studies in wheelchair propulsion using either an instrumented ergometer or using ambulant measurement-wheels have shown an increase in mechanical efficiency in combination with a longer stroke and reduced frequency for both able-bodied participants and people with a disability [16]–[23]. In these studies practice interventions ranged from three to twelve weeks and one study followed persons with spinal cord injury observationally over the course of rehabilitation [24]. Two (combined) studies evaluated the initial first 12 min of wheelchair propulsion practice performed by nine novice able-bodied participants on a wheelchair ergometer [25], [26]. These two studies showed that propulsion technique measures, like a reduced push frequency and an increased peak torque, changed already during the first 12 min of practice, however a reduction of energy expenditure was not found.

The current study will revisit the initial motor learning process and evaluate the changes in energy expenditure and propulsion technique over this short 12 min period. Three key differences with respect to the earlier studies will further our understanding of changes in mechanical efficiency and its relation to propulsion technique. The first is the use of a treadmill in combination with ambulant measurement wheels instead of a stationary ergometer [27]. Due to the necessity to combine both steering and propulsion the use of a motor driven treadmill is expected to be more demanding, leading to an increased movement variability and subsequently having more degrees of freedom that need to be learned during practice and thus being more similar to over-ground wheelchair propulsion. Second, the availability of a large sample of 70 able-bodied participants, will make it possible to not only examine the changes over time of energy expenditure and propulsion technique, but also to examine the interaction(s) between propulsion technique and biomechanical variables using multi-level regression analyses. Finally, the larger groups allows for studying possible differences in motor learning capacity between participants [28]–[30].

Therefore the objective of the current study was to establish whether the motor learning process during the first 12 min of handrim wheelchair propulsion would lead to 1) an increased mechanical efficiency and a longer-slower movement rhythm; 2) an association of propulsion technique to mechanical efficiency within and between participants; 3) differences between participants in the motor learning process based on the degree of improvement in mechanical efficiency.

The typical changes of propulsion technique that are found after longer practice interventions such as a reduction in frequency and increase in contact angle and reduction of negative work are expected to already be seen within the 12-min practice intervention [16]–[23], [25], [26]. As a consequence of a more effective propulsion technique a directly increased mechanical efficiency is expected.

II. Methods

A. Participants

After having given written informed consent, a convenience sample of 70 able-bodied men participated in the study. To compare our results with previous research the criteria for inclusion were male, between 18–65 years, no prior experience in wheelchair propulsion, and absence of any medical contra-indications [16], [18], [19], [25], [31]. The participants had a mean age of 22.8 years ($std = 3.6$), a mean body mass of 80.2 kg ($std = 11.4$), and a mean height of 1.87 m ($std = 0.07$). All participants signed an informed consent. The study was performed according to the guidelines of the Local Ethics Committee of the center for Human Movement Sciences, University Medical Center Groningen, University of Groningen.

B. Protocol

The single session 16-min experiment was conducted on a level treadmill of 2.4 m length by 1.2 m width (Forcelink BV, Culemborg, The Netherlands) in the same experimental wheelchair (Double Performance BV, Gouda, The Netherlands) with 24-in measurement wheels. Each participant performed three 4-min exercise blocks at a fixed submaximal power output of 0.20 W/kg body weight, with 2 min of rest in between blocks. This low intensity was chosen to minimize fatigue or training effects and focus primarily on motor learning. The first 40 s were used to get the treadmill up to a speed of 1.11 m/s (4 km/h). Participants received no specific instructions other than to stay on the treadmill using the hand rims. Apart from rolling resistance, the required power output was imposed by adding mass to a pulley system. Pulley mass was determined from the results of an individual wheelchair drag test [5], [32].

C. Measurement Wheels

The experimental wheelchair was kept constant (e.g., tire pressure was inspected before testing), and no individual changes were made to the wheelchair for the different participants. The regular rear wheels of the standardized wheelchair were replaced with two instrumented wheels; on the left the Optipush (Max Mobility, LLC, Antioch, TN, USA) and on the right the Smartwheel (Three-Rivers Holdings, Mesa, AZ, USA). Both wheels measure 3-D forces and torques applied to the hand rim, combined with the angle under which the wheel is rotated. Data were wirelessly transferred to a laptop at 200 Hz (Optipush) and 240 Hz (Smartwheel). Both wheels were synchronised by an electronic pulse at the start of each measurement [27]. Data from the Optipush were primarily used in the analyses, only when the Optipush data were lacking they were replaced with Smartwheel data. Data of both wheels show good comparability, with an intra-class correlation (ICC) of 0.89 for mean power output and ICC's higher then 0.90 for propulsion technique characteristics [27].

D. Energy Expenditure

Oxygen consumption (VO2) was continuously measured during the 16-min experiment using breath-by-breath open circuit spirometry (Oxycon Pro-Delta, Jaeger, Hoechberg, Germany). The gas analyzer was calibrated using a Jaeger 5l

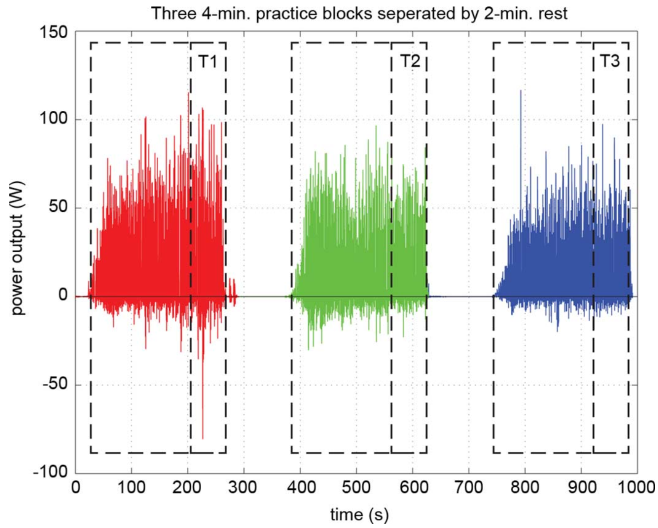


Fig. 1. Example of the power output over the whole practice protocol for one participant. Three 4-min practice blocks are separated by 2 min of rest. Data was analyzed at the last minute of each practice-bock, shown as T1, T2, and T3, being the fourth, eighth, and twelfth minute of practice.

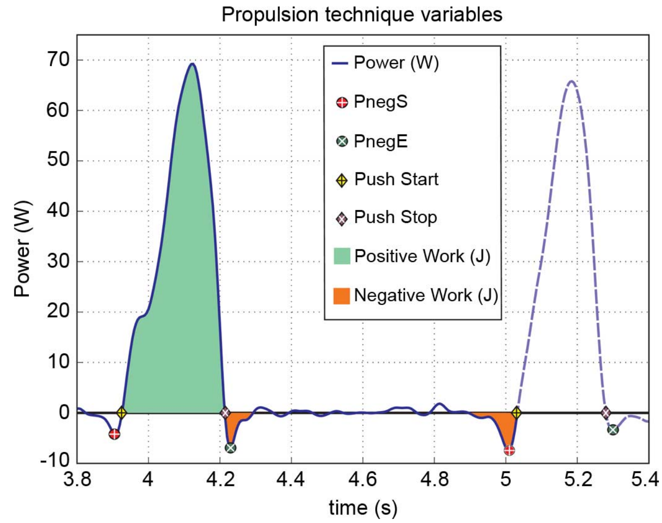


Fig. 2. Definition of the analyzed propulsion technique variables. Plotted is the power production over time. Note the push detection of the start and end of a push and the negative dips before (PnegS) and after the push (PnegE).

syringe, room air and a calibration gas mixture. Data collected over the fourth minute of each exercise block were averaged and taken to reflect physiological steady-state wheelchair propulsion. From the VO2 (L/min), VCO2 (L/min), and respiratory exchange ratio (VCO2/VO2) the energy expenditure was determined using the formula proposed by Garby and Astrup [33].

E. Data Analysis

The data from the instrumented wheels were further analyzed using custom-written MATLAB routines. Data of all three blocks including the rest periods were collected in one continuous measurement (Fig. 1). To be sure of stable, steady-state propulsion, each last minute from the three 4-min blocks (T1-T2-T3) was used for the analysis. Per participant and block, nine parameters of data output were further used in the analysis. These were the x, y, and z components of force (N) and torque (Nm) as expressed by the wheels in their local coordinate systems, angle (rad), time (s), and sample number. Individual pushes were defined as each period of continuous positive torque around the wheel axis with a positive minimum of at least 1 Nm. Over the identified pushes biomechanical variables were calculated and subsequently averaged over all pushes within the fourth minute of each practice block per participant. Calculated variables are defined in Table I and Fig. 2. Over these variables the coefficient of variation (CV), i.e., the ratio of the individual standard deviation to the mean for each practice-block, was calculated to see if participants would reduce in variability because of motor learning.

F. Statistics

For each propulsion-technique variable and its CV a repeated-measures Anova was performed, followed by a post-hoc analysis to see which blocks differed from each other. Significance for the repeated measures Anova was set at a $p < 0.05$ and by use of the Bonferroni correction the significance for the post hoc t-test between any two different blocks was $p < 0.017$ [34]. Effect size was calculated using partial eta-squared (η_p^2) and interpreted as small (≥ 0.01), medium (≥ 0.06), or large (≥ 0.14) [35].

To evaluate the relationship between propulsion technique and mechanical efficiency multi-level analysis was performed using MLWin [36]. The different propulsion technique variables (Table I) were first studied univariate in relation to the dependent variable mechanical efficiency. The variables that related significantly with $p < 0.05$ to mechanical efficiency were used for multivariate analysis. Since the different propulsion variables are not all independent, but are theoretically linked to each other they are not expected to all remain in the multivariate model. First, all the variables that were significant in the univariate model were added to the multivariate model and then, using a backward regression procedure, one-by-one the nonsignificant terms were removed to come to the final model. This final model shows the relation of the resulting propulsion technique variables in the model to mechanical efficiency over all observations of participants and blocks.

To examine whether a change in propulsion technique relates to a change in mechanical efficiency a second multi-level analysis was done on the delta scores, i.e., the differences between the blocks (T2-T1 and T3-T2). Here the same method was applied as above to see which variables fitted the model best. The final delta model shows if changes in propulsion technique within participants relate to changes in mechanical efficiency.

Finally, we examined motor learning differences between participants. The group was split in two, based on a relative increase in mechanical efficiency of larger then 10% between T1 and T3, to ensure that differences in learning were above the natural expected variation. The two groups were subsequently compared on their mechanical efficiency and the most important propulsion technique variables (as shown by the multi-level model) over all three practice-blocks using repeated-measures Anova, with the interaction between group $(= 10\% or > 10\%)$ and practice-blocks as the most important outcome.

TABLE I
PROPULSION TECHNIQUE VARIABLES

Variable:	**Description:**	**Equation:**
Energy expenditure (W)	Calculated from the oxygen uptake and respiratory exchange ratio according to Garby and Astrup [33]	((4.94*RER+16.04)*(1000*VO2))/ 60
Mechanical efficiency (%)	The percentage of internal power used for external power delivered at the wheels	Mean power output/ Energy expenditure
Push time (s)	Time from the start of positive torque to the stop of positive torque for an individual push.	$t_{end}(i) - t_{start}(i)$
Cycle time (s)	Time from the start of positive torque to the next start of positive torque.	$t_{end}(i) - t_{end}(i-1)$
Frequency (push/min)	The number of complete pushes per minute.	$N_{pushes}/\Delta t$
Pos. Work/push (J)	The power integrated over the Contact angle of the push.	$\sum_{start:end}(Tz \bullet \Delta Ø)$
Neg. Work/cycle (J)	The power integrated over the wheel rotation angle during the recovery phase	$\sum_{end:start}(Tz \bullet \Delta Ø)$
Net Work/cycle (J)	The mean power output divided by the push frequency	$\text{Mean}(P_{out})$ / Frequency
%NegWork/cycle (%)	The Neg. work per cycle relative to the Net Work/cycle	(Neg. Work/cycle / (Net Work/cycle))*100
PnegS (W)	The minimum power preceding the push phase	$\text{Min}_{<start}$ (Power)
PnegE (W)	The minimum power following the push phase	$\text{Min}_{>end}$(Power)
Contact angle (º)	Angle at the end of a push minus the angle at the start.	$Ø_{end}(i)-Ø_{start}(i)$
Slope (Nm/s)	The rate of rise from the start of the push phase to the maximum delivered torque around the axle	MaxTorque/Δt
$Ftot_{mean}$ (N)	3d mean force within the push phase	$\text{Mean}_{start:end}(Fx^2+Fy^2+Fz^2)^{0.5}$
$Ftot_{peak}$ (N)	3d peak force within the push phase	$\text{Max}_{start:end}(Fx^2+Fy^2+Fz^2)^{0.5}$
FeF_{mean} (%)	Mean Fraction effective Force	$\text{Mean}_{start:end}(F_{tangential}/F_{total})$
FeF_{peak} (%)	Peak Fraction effective Force	$\text{Max}_{start:end}(F_{tangential}/F_{total})$

Abbrevations: t, time(s); $_{start}$(i), start of the current push (sample); $_{end}$(i), end of the current push (sample); Ø, angle (rad); Fx, Fy and Fz, force components (N); Tz, torque around wheel axle (Nm);

III. Results

All participants were able to complete the whole protocol without incidents. The Optipush data (left side) were used 66 times, while Smartwheel data (right side) were used four times. On average participants practiced at a power output of 17.4W ($std = 3.67$). Fig. 1 shows a typical example of the power production over the whole measurement period of one participant, while Fig. 3 gives a more detailed view of the changes in torque production at the three practice-blocks. Table II lists the results for mechanical efficiency and the propulsion technique variables over time (T1-T3).

A. Energy Expenditure

The energy expenditure as calculated from the oxygen consumption significantly reduced (from 371 W to 345 W to 332 W), accounting for an increased mechanical efficiency (from 4.8% to 5.3% to 5.5%) over the three blocks (Table II). For both measures the post-hoc comparison showed statistically significant changes over time, i.e., a higher mechanical efficiency each next block.

B. Propulsion Technique

A significant increase in push time (from 0.26 s to 0.29 s to 0.31 s) and cycle time (from 0.91 s to 1.00 s to 1.05 s) was found (Fig. 3.). The increase in cycle time over the three practice blocks was associated with a reduced frequency (from 73.0 to 66.0 to 62.2 pushes/min). The positive work per push went up (from 8.56 J to 9.36 J to 9.76 J) from T1 to T3, while the amount of negative work per cycle reduced (from $-0.85J$ to -0.68 to $-0.51J$) with practice, which leads to an increased net work per cycle. The reduced amount of negative work was achieved by significantly reducing both the negative phases before the push (from $-8.$ W to -6.1 W to -5.5) W and after the push (from -5.0 W to -3.9 W to -2.8 W). Fig. 3 shows the change in propulsion technique of one participant over the three blocks.

The increased work per push was achieved by an increase of the contact angle on the hand rim (from 55.1° to 61.1° to 64.5°), rather than an increase of force application, i.e., no increase of either $\mathrm{Ftot}_{\mathrm{mean}}$ or $\mathrm{Ftot}_{\mathrm{peak}}$ was found. The mean push force $\mathrm{Ftot}_{\mathrm{mean}}$ actually went down (from 47.2 N to 45.3 N to 45.0 N), which was a significant main effect, but post-hoc tests only showed a significant change between the first and last block. The slope, i.e., the rise of torque per second, significantly reduced (from 106.2 Nm/s to 90.1 Nm/s to 83.6 Nm/s) showing that

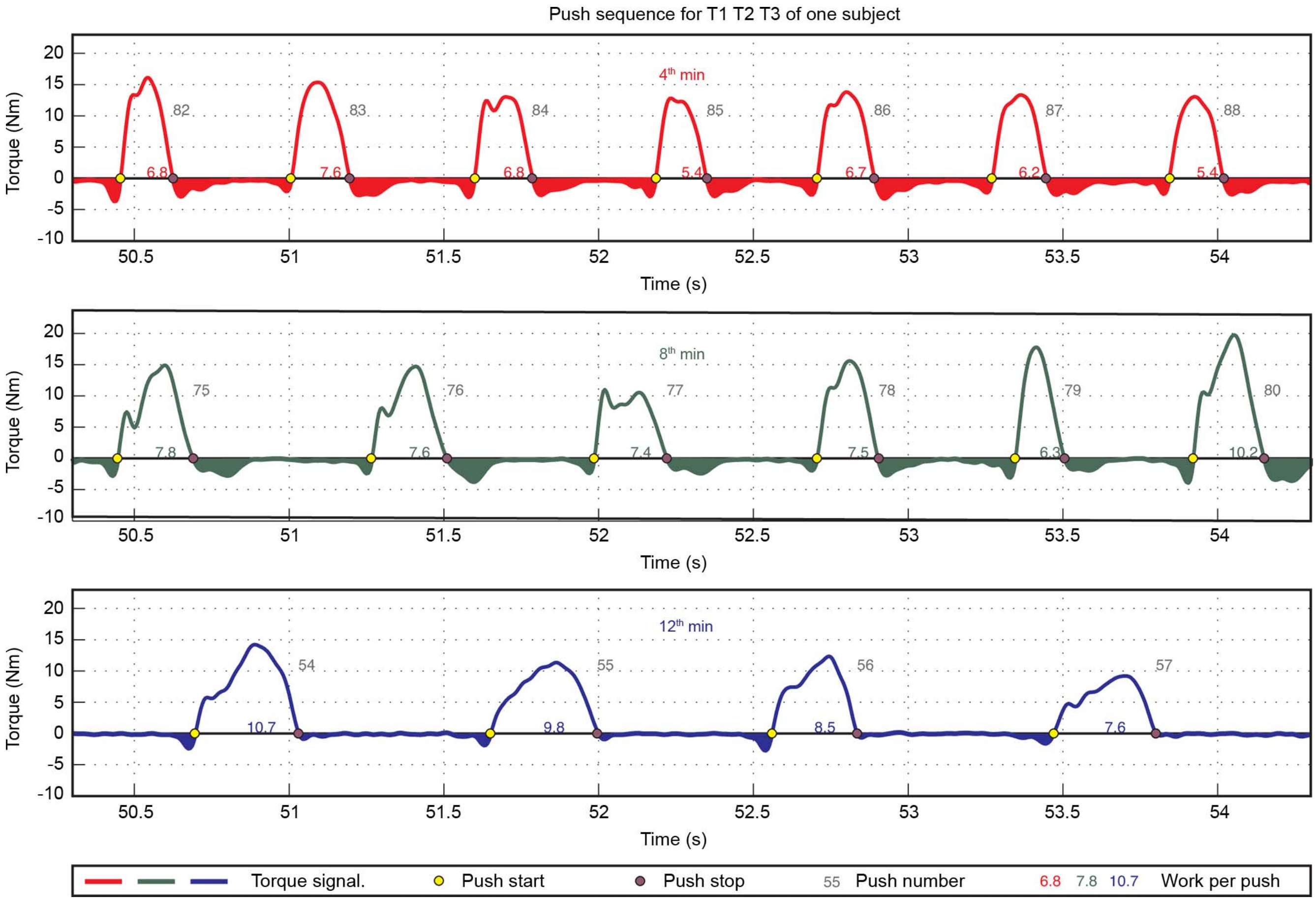


Fig. 3. Typical example of the individual torque signal for the fourth (T1), eighth (T2), and twelfth (T3) minute. Over the whole group participants show a reduction in frequency and increase in work per push. Further the negative work per cycle is reduced for each next measurement period, depicted as the filled surface below zero.

the peak torque was reached over a longer range of both time and angle. The mean fraction effective force showed a significant main effect (from 67.2% to 69.2% to 69.0%), but post-hoc tests only showed a significant difference between the first and second block. The peak fraction effective force did not change significantly.

C. Within Subject Variability

Participants significantly reduced the coefficient of variation for the positive work per push, slope, contact angle, $\mathrm{Ftot}_{\mathrm{mean}}$, cycle time, $\mathrm{Ftot}_{\mathrm{peak}}$, and push time. The largest reduction was found in the positive work per push (from 24.9% to 22.1% to 20.1%), which is a 19.2% reduction of the between cycle variability.

D. Relationship of Propulsion Technique To Mechanical Efficiency

Table III lists the univariate relation of the different propulsion technique variables to mechanical efficiency. Table IV shows the final multivariate models for the three practice-blocks and their delta values. In the final multivariate model the percentage negative work per cycle and the contact angle related significantly to mechanical efficiency, explaining together 49% of the variance in mechanical efficiency (Table IV).

The change model based on the delta-scores showed that a change of percentage negative work per cycle, contact angle, frequency and net work per cycle related to a change in gross ME, together explaining 35% of the variance in change of mechanical efficiency (Table IV).

E. Individual Differences in Motor Learning

From the 70 participants 46 increased their mechanical efficiency with more then 10% between T1 and T3 whereas 24 did not. The repeated measures Anova (Fig. 4, Table V) showed interaction effect between group and practice-blocks ($p < 0.0001$). The 24 non-improvers had a significant higher mechanical efficiency at T1 compared to the improving group (5.6% versus 4.4%, $p < 0.001$). At T2, because of the Bonferroni correction, the difference between groups almost reached significance (5.7% versus 5.1%, $p = 0.026$). At T3 the non-improving and improving group were equal (5.5% versus 5.5%, $p < 0.97$). The four propulsion technique variables, i.e., percentage negative work per cycle, contact angle, frequency and net work per cycle, that were identified by the multi-level analysis as being strongly related to mechanical efficiency, also

TABLE II
MEANS AND STANDARD DEVIATIONS OF ALL ANALYZED TECHNIQUE PARAMETERS FOR THE FINAL MINUTE OF EACH OF THE THREE 4-MIN PRACTICE BLOCKS (T1, T2, T3). LAST COLUMN SHOWS THE P-VALUE OF THE REPEATED MEASURES ANOVA. * NOTES A SIGNIFICANT POST-HOC DIFFERENCE BETWEEN ALL THREE BLOCKS. + REPRESENTS A SIGNIFICANT VALUE FOR THE MAIN EFFECT, BUT NOT FOR ALL POST-HOC DIFFERENCES. TRENDS OF SIGNIFICANT CHANGES OVER TIME ARE SHOWN WITH ARROWS

Wheels + Oxycon (N=70)	T1 Mean	Std	T2 Mean	Std	T3 Mean	Std	F (2,138)	P	η_p^2
Energy expenditure (W)	371	108	345	100	332	85	19.46	<0.001*,↓	0.22
Mechanical efficiency (%)	4.8	1.2	5.3	1.3	5.5	1.1	33.27	<0.001*,↑	0.33
Push time (s)	0.26	0.06	0.29	0.06	0.31	0.06	45.89	<0.001*,↑	0.40
Cycle time (s)	0.91	0.29	1.00	0.32	1.05	0.31	28.69	<0.001*,↑	0.29
Frequency (push/min)	73.0	20.9	66.0	18.6	62.2	17.2	27.44	<0.001*,↓	0.28
Pos. Work/push (J)	8.56	2.94	9.36	3.05	9.76	2.93	28.67	<0.001*,↑	0.29
Neg. Work/cycle (J)	-0.85	0.89	-0.68	0.86	-0.51	0.69	19.04	<0.001*,↓	0.22
Net Work/cycle (J)	7.67	3.07	8.62	3.19	9.19	3.09	34.59	<0.001*,↑	0.33
PnegS (W)	-8.1	4.4	-6.1	3.3	-5.5	3.1	43.18	<0.001*,↓	0.38
PnegE (W)	-5.0	5.4	-3.9	4.8	-2.8	3.4	21.49	<0.001*,↓	0.24
Contact angle (°)	55.1	13.0	61.1	12.5	64.5	12.9	41.87	<0.001*,↑	0.38
Slope (Nm/s)	106.2	42.8	90.1	31.6	83.6	30.4	25.43	<0.001*,↓	0.27
F_{mean} (N)	47.2	14.1	45.3	12.2	45.0	11.5	4.18	0.02^{+}, ↓	0.06
F_{peak} (N)	76.4	24.2	73.7	21.5	73.8	19.9	2.35	0.1	-
FeF_{mean} (%)	67.19	8.46	69.19	9.28	69.00	8.97	4.05	0.02^{+}, ↑	0.06
FeF_{max} (%)	96.3	13.3	98.3	15.5	98.5	15.7	1.47	0.23	-

TABLE III
UNIVARIATE MULTI-LEVEL MODELS, WITH MECHANICAL EFFICIENCY AS THE DEPENDENT VARIABLE

	Constant	SE	Beta	SE	p-value	Explained Var. (%)
Empty	5.20	0.13	-	-	-	-
Neg. Work/cycle (J)	5.89	0.13	1.01	0.09	<0.001	31.43
PnegE (W)	5.85	0.13	0.17	0.02	<0.001	30.97
Frequency (push/min)	7.53	0.27	-0.04	0.00	<0.001	27.95
PnegS (W)	6.36	0.16	0.18	0.02	<0.001	27.89
Contact angle (°)	2.11	0.31	0.05	0.01	<0.001	25.72
Push time (s)	2.23	0.31	10.31	1.00	<0.001	23.23
Slope (Nm/s)	6.61	0.21	-0.02	0.00	<0.001	18.37
Cycle time (s)	3.14	0.29	2.08	0.26	<0.001	18.04
Net Work/cycle (J)	2.99	0.25	0.26	0.03	<0.001	17.32
Pos. Work/push (J)	3.01	0.31	0.24	0.03	<0.001	4.72
FeF_{mean} (%)	3.90	0.66	0.02	0.01	<0.05	1.57
F_{mean} (N)	6.04	0.38	-0.02	0.01	<0.05	0.39

showed an interaction effect between group and practice-blocks ($p < 0.001$).

IV. DISCUSSION

Aim of the present study was to evaluate the change in mechanical efficiency and propulsion technique during the initial skill acquisition of a steady-state wheelchair propulsion task, using able-bodied participants. Within the 12 min of practice participants learned to deliver the same power output using less energy and concomitantly changed their propulsion technique. Furthermore the increased mechanical efficiency related to the changed propulsion technique of the participants. Finally, it was shown that two different learning groups could be identified, a group that not or only slightly improved their mechanical efficiency and one that improved much more during the three 4-min practice-blocks. The no-improvers already had a higher mechanical efficiency and a better propulsion technique compared to the improving group at the first time of measurement.

TABLE IV
MULTIVARIATE MULTI-LEVEL MODELS, WITH MECHANICAL EFFICIENCY AS THE DEPENDENT VARIABLE

ME	Normal values				Delta values			
	Beta	SE	p-value	R^2	Beta	SE	p-value	R^2
Constant	4.231	0.356			0.122	0.068		
% Neg work/cycle	-0.063	0.007	<0.0001		-0.060	0.013	<0.0001	
Contact angle	1.414	0.305	<0.0001	47%	1.318	0.666	<0.05	
Freq(min)	-	-	-		0.028	0.009	<0.05	
Net Work/cycle	-	-	-		0.163	0.071	<0.05	35%

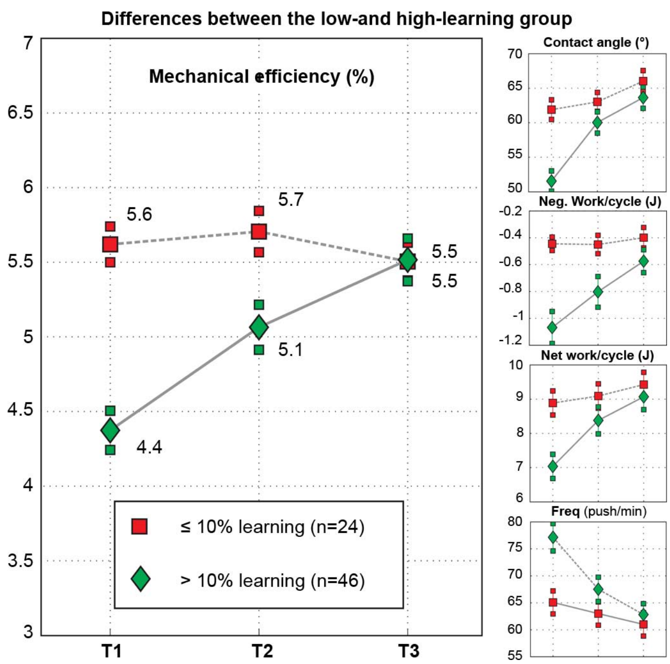


Fig. 4. Interaction effects of group and practice-blocks for mechanical efficiency and the most important propulsion technique variables. The = 10%-increase group already had a higher mechanical efficiency and a better propulsion technique at the start. The error bars depict the standard error of measurement. T1, T2, T3 on the x-axis represent the fourth, eighth, and twelfth minute of practice in all graphs.

Where previously the study of De Groot *et al.* [25] did not observe a reduction of energy cost, i.e., an increased mechanical efficiency, the current study did find these changes over a very short practice period. Important differences of the current study with that of De Groot *et al.* [25] is the much larger number of participants (N=70 versus N=9) and the use of a wheelchair on a treadmill instead of an ergometer. It was hypothesized that the combination of propulsion with steering would make propulsion on the treadmill a more challenging task then pushing on a stationary ergometer. One clear difference that in our view relates to the increased difficulty of the treadmill is the higher push frequency of the participants. Compared to the push frequency on the ergometer (57–53-51 Pushes/min) the frequency on the treadmill was higher (73–66-62 Pushes/min), despite the lower power output (22.5 W versus 17.2 W, respectively). This is contrary to the findings of a different study with two levels of intensity on the ergometer, which found that a higher power output (0.15–0.25 W) showed a higher push frequency (41.7–46.4 Pushes/min) [16]. Apparently participants propel at a higher frequency on the treadmill to maintain a better control over the directional change of the wheelchair, which has to be aligned with the 1.2 m width of the treadmill. Since this extra steering component relies more on control it might be more susceptible to learning processes that reduce and compensate for bilateral asymmetries, explaining the increased learning effects found in the current study.

The larger sample size leads to more statistical power. The group of 70 participants offered a unique opportunity to find group level effects, allowed the use of multi-level analysis within and between subjects and gave the possibility to discriminate between differences in motor learning. The changes in propulsion technique that were found together with the reduced energy cost are discussed in relation to each other below.

At steady-state wheelchair propulsion with a fixed speed of the treadmill, the average power output remains constant. Propulsion technique can change but in the end the average power output must be maintained to keep rolling on the treadmill. Because of this constant power output the propulsion technique parameters are linked to each other and change in one will be reflected in the other.

First power output is performed through the multiplication of work per cycle and the frequency of the pushes [37]. Any reduction of push frequency will have to go along with increased work per cycle and vice versa to maintain the power output necessary at a certain treadmill speed. As expected from earlier work on wheelchair propulsion and motor learning the participants indeed learned a "longer-slower" movement pattern [16]–[23]. An increased work per push was associated with a reduced push frequency.

Second, the work per push is the integration of positive torque around the axle over the angle through which it rotates. Any combination of angle and torque can account for the work done within a push. Although this gives a large range of performance possibilities probably some are more suitable to perform in a less straining, more energy efficient way. As expected from the "longer-slower" movement hypothesis [11] participants learned to use a prolonged trajectory of the hand in contact with the hand rim, resulting in a longer push time. Interestingly this is

TABLE V
MEANS AND STANDARD DEVIATIONS OF MECHANICAL EFFICIENCY AND THE MOST IMPORTANT TECHNIQUE PARAMETERS FOR THE FINAL MINUTE OF EACH OF THE THREE 4-MIN PRACTICE BLOCKS (T1, T2, T3). THE T-TEST SHOWS THE DIFFERENCES BETWEEN THE GROUPS WITHIN A PRACTICE BLOCK. THE INTERACTION EFFECT SHOWN BY THE REPEATED MEASURES ANOVA SHOWS THE LEARNING DIFFERENCES. * NOTES A SIGNIFICANT EFFECT OF $p < 0.001$

		T1			**T2**			**T3**			**F time**		**F group**		**F time*group**	
		Mean	**Std**	**p-ttest**	**Mean**	**Std**	**p-ttest**	**Mean**	**Std**	**p-ttest**	**(2, 136)**	η_p^2	**(1, 136)**	η_p^2	**(2, 136)**	η_p^2
Mechanical efficiency (%)	<10%	4.37	1.10	0.000	5.06	1.26	0.042	5.52	1.20	0.970	48.61*	0.42	5.15*	0.42	32.79*	0.33
	>10%	5.62	1.00		5.71	1.16		5.51	1.05							
Neg. Work/cycle (J)	<10%	-0.44	0.42	0.005	-0.45	0.57	0.102	-0.40	0.64	0.317	21.07*	0.24	4.07*	0.35	8.35*	0.11
	>10%	-1.07	1.00		-0.80	0.95		-0.57	0.71							
Contact angle (º)	<10%	61.90	11.89	0.001	63.03	11.47	0.344	66.03	12.78	0.465	46.86*	0.41	3.23	0.22	9.22*	0.12
	>10%	51.55	12.30		60.03	12.93		63.64	12.98							
Frequency (push/min)	<10%	65.06	17.89	0.020	63.00	18.05	0.340	60.99	18.16	0.677	29.53*	0.30	1.96	0.16	6.26*	0.08
	>10%	77.15	21.31		67.50	18.84		62.82	16.85							
Net Work/cycle (J)	<10%	8.89	2.94	0.015	9.09	2.98	0.379	9.43	3.01	0.652	38.60*	0.36	1.69	0.24	9.00*	0.12
	>10%	7.04	2.96		8.38	3.30		9.07	3.16							

opposite to the results found in the de Groot *et al.* study, where the increased work per push was attributed to an increase in peak torque and no significant change in push time was found [25].

Third, the increase of contact angle led to a reduction of the slope, the rise of torque per second, which meant that the build up of force became more gradual, possibly reducing stress on the upper extremity and reducing the risk of repetitive strain [38], [39].

Finally, participants learned to reduce the amount of negative work during the coupling and decoupling of the hand to the rim. Thus, in combination with the reduced frequency, the amount of (de)couplings reduced in both number and magnitude, leading to less negative work done by the participants. Because the negative work did not have to be compensated with positive work in total less work needs to be done to maintain the same power output.

For a number of propulsion technique variables the coefficient of variation reduced. In our view the reduction of variability in the positive work per push is the most important one since it combines others variables like contact angle and mean and peak forces, of which the coefficient of variation also reduced. The reduced variability between cycles might reflect motor learning, leading to less error within cycles (matching the speed of the treadmill) and possibly less error between left- and right-hand push differences (compensations for directional change).

The above-described changes in propulsion technique theoretically imply a reduction in the energy cost of the user. Using multi-level modeling this relationship was further explored to see which technique changes related most to mechanical efficiency. Both multi-level models indeed showed a relation between propulsion technique and mechanical efficiency. Although this relation was assumed in earlier studies [16]–[23] the current model results make a further step in understanding the relation between the components of skill of execution and energy cost. In light of the variability in personal characteristics and the fact that the wheelchair was not adapted to the individual anthropometry of each participant the explained variance of 47% by propulsion technique in mechanical efficiency is a meaningful result. The propulsion technique variables that together related significantly to mechanical efficiency were the percentage negative work per cycle and contact angle. Reduced losses because of negative work and a larger contact angle relate to a higher mechanical efficiency as was expected.

For the delta scores the change in propulsion technique predicted 35% of the observed change in mechanical efficiency. Besides the variables percentage negative work per cycle and contact angle, the push frequency and the net work per cycle also contributed to mechanical efficiency. The percentage negative work per cycle and contact angle changed in the same direction as the previous model. The direction of frequency on the other hand is counterintuitive because here also an increase is predicted to contribute positively to mechanical efficiency. However the other changes should already have led to a reduction in frequency, which makes this outcome harder to interpret. Finally an increase in the net work per cycle increases the mechanical efficiency as expected. The change in both models was nearly identical, and therefore we conclude that the relationship between propulsion technique and mechanical efficiency was mainly based on the within-participant variance instead of between-participant variance. This implicates that persons who are able to improve their propulsion technique can expect an improvement in their mechanical efficiency.

To identify different types of learners two groups were formed on the basis of change in mechanical efficiency ($> 10\%$) between T1 and T3, and compared on their mechanical efficiency and propulsion technique over all practice-blocks. The improvers, with about 2/3 of the participants started with a lower mechanical efficiency and a less optimal propulsion technique then the nonimprovers. Possibly the improving group still had more room to increase in proficiency of the propulsion skill, while the more proficient group at the start, i.e., the low-learning group was already closer to their optimum [40]. Whether the low-increase group learned faster and already had adapted in the fourth minute, or that they had this higher mechanical efficiency from the start cannot be concluded from the present study. How individual differences impact motor learning of a cyclic task like wheelchair propulsion is an important topic for future research so rehabilitation programs can be better tailored to the needs of novice individual wheelchair-users.

Although the clinical relevance lies with people in a wheelchair during early rehabilitation, it was thought necessary to use able-bodied participants to get a better view on technique changes in this early stage of learning a new task, since the results are not confounded by the heterogeneity of wheelchair-users like lesion level or comorbidities after trauma. The current study shows that a better propulsion technique relates to energy cost, which is an important factor in daily life for those with a limited physical capacity [24]. However, the relatively young age of our participants might make inferences for wheelchair-users harder. Furthermore 12 min at a fixed speed of 4 km/h at 0.20 W/kg might be too high a load to be a feasible practice method during early rehabilitation especially for those with a tetraplegia [41].

Since only male participants were recruited, we do not know whether the found changes in mechanical efficiency and propulsion technique would be of the same order and magnitude in female participants. We expect similar trends in female participants, yet at relative different levels of timing and kinetics as well as metabolic cost. Overall the motor learning differences found in our relatively homogeneous group of male participants only further stresses the need for more individualized assessment of motor learning, where female participants should also be studied.

Altogether, over the course of 12 min of wheelchair propulsion participants learned a more favorable push strategy. It is an important finding that participants, without getting any specific feedback or modified training program already find a more optimal wheelchair propulsion technique during the initial minutes of practice. This further supports the view of Sparrow and Newell that the human system is continuously in search of the most energy efficient solution within the constraints of the task [11]. The observed transition to a longer-slower movement pattern found in other cyclical motions is also observed as a consequence of motor learning in hand rim wheelchair propulsion over this short practice period. Future research should take these early learning adaptations into account when evaluating different interventions on motor learning over longer timescales.

V. Conclusion

Over the first 12 min of practice naive able-bodied participants increased their mechanical efficiency and changed their propulsion technique. The propulsion technique of the participants changed from a high frequency mode with a lot of negative work to a longer-slower movement pattern with less power loss. This change in propulsion technique related to an increased mechanical efficiency of the participants and thus a lower physical strain. These findings link propulsion technique to mechanical efficiency supporting the importance of a correct propulsion technique for wheelchair users. Furthermore differences in baseline efficiency and propulsion technique were shown to affect the motor learning process. Individual motor learning differences are important to take into account for rehabilitation programs.

Acknowledgment

R. J. K. Vegter was involved in the conception of the research project, the design, the execution, the analysis and the interpretation thereof and the writing of the manuscript. C. J. Lamoth and S. de Groot were involved in the design, analysis and interpretation of the data analysis and writing of the manuscript. H. E. J. Veeger contributed to the conception of the study, interpretation of the data analysis and revising the manuscript. L. van der Woude participated in the conception and organization of the study, interpretation of the data analysis, and revising of the manuscript. All authors read and approved the manuscript.

References

[1] L. H. van der Woude, A. J. Dallmeijer, T. W. Janssen, and D. Veeger, "Alternative modes of manual wheelchair ambulation: An overview," *Am. J. Phys. Med. Rehabil.*, vol. 80, pp. 765–77, Oct. 2001.

[2] T. A. Dyson-Hudson and S. C. Kirshblum, "Shoulder pain in chronic spinal cord injury, part I: Epidemiology, etiology, and pathomechanics," *J. Spinal Cord Med.*, vol. 27, pp. 4–17, 2004.

[3] D. A. Ballinger, D. H. Rintala, and K. A. Hart, "The relation of shoulder pain and range-of-motion problems to functional limitations, disability, and perceived health of men with spinal cord injury: A multifaceted longitudinal study," *Arch. Phys. Med. Rehabil.*, pp. 1575–1581, 2000.

[4] W. E. Pentland and L. T. Twomey, "Upper limb function in persons with long term paraplegia and implications for independence: Part I," *Paraplegia*, pp. 211–218, 1994.

[5] L. H. van der Woude, G. de Groot, A. P. Hollander, G. J. van Ingen Schenau, and R. H. Rozendal, "Wheelchair ergonomics and physiological testing of prototypes," *Ergonom.*, vol. 29, pp. 1561–73, Dec. 1986.

[6] L. H. van der Woude, K. M. Hendrich, H. E. Veeger, G. J. van Ingen Schenau, R. H. Rozendal, G. de Groot, and A. P. Hollander, "Manual wheelchair propulsion: Effects of power output on physiology and technique," *Med. Sci. Sports Exercise*, vol. 20, pp. 70–8, Feb. 1988.

[7] M. L. Boninger, R. L. Waters, T. Chase, M. P. J. M. Dijkers, H. Gellman, R. J. Gironda, B. Goldstein, S. Johnson-Taylor, A. M. Koontz, and S. L. McDowell, "Preservation of upper limb function following spinal cord injury: A clinical practice guideline for health-care professionals," *J. Spinal Cord Med.*, vol. 28, no. 5, pp. 434–470.

[8] B. Almasbakk, H. T. Whiting, and J. Helgerud, "The efficient learner," *Biol. Cybern.*, vol. 84, pp. 75–73, 2001.

[9] L. H. van der Woude, H. E. Veeger, and R. H. Rozendal, "Propulsion technique in hand rim wheelchair ambulation," *J. Med. Eng. Technol.*, vol. 13, pp. 136–41, Jan.-Apr. 1989.

[10] W. A. Sparrow, *The Efficiency of Skilled Performance*. New York: Taylor Francis, 1983, pp. 237–261.

[11] W. Sparrow and K. Newell, "Metabolic energy expenditure and the regulation of movement economy," *Psychonomic Bull. Rev.*, vol. 5, pp. 173–196, 1998.

[12] B. S. Lay, W. A. Sparrow, K. M. Hughes, and N. J. O'Dwyer, "Practice effects on coordination and control, metabolic energy expenditure, and muscle activation," *Hum. Mov. Sci.*, vol. 21, pp. 807–30, Dec. 2002.

[13] B. Galna and W. A. Sparrow, "Learning to minimize energy costs and maximize mechanical work in a bimanual coordination task," *J. Mot. Behav.*, vol. 38, pp. 411–22, Nov. 2006.

[14] W. A. Sparrow and K. M. Newell, "Energy expenditure and motor performance relationships in humans learning a motor task," *Psychophysiology*, vol. 31, pp. 338–46, Jul. 1994.

[15] W. A. Sparrow, "Mechanical efficiency and metabolic cost as measures of learning a novel gross motor task," *J. Motor Behav.*, vol. 19, no. 2, pp. 240–264, 1987.

[16] S. De Groot, D. H. Veeger, A. P. Hollander, and L. H. van der Woude, "Wheelchair propulsion technique and mechanical efficiency after 3 wk of practice," *Med. Sci. Sports Exerc.*, vol. 34, pp. 756–66, May 2002.

[17] S. de Groot, H. E. Veeger, A. P. Hollander, and L. H. van der Woude, "Influence of task complexity on mechanical efficiency and propulsion technique during learning of hand rim wheelchair propulsion," *Med. Eng. Phys.*, vol. 27, pp. 41–9, Jan. 2005.

[18] S. de Groot, M. de Bruin, S. P. Noomen, and L. H. van der Woude, "Mechanical efficiency and propulsion technique after 7 weeks of low-intensity wheelchair training," *Clin. Biomech. (Bristol, Avon)*, vol. 23, pp. 434–41, May 2008.

[19] R. Van Den Berg, S. De Groot, K. M. Swart, and L. H. Van Der Woude, “Physical capacity after 7 weeks of low-intensity wheelchair training,” *Disabil. Rehabil.*, vol. 32, pp. 2244–52, Feb. 2010.

[20] J. P. Lenton, L. H. V. Van Der Woude, N. E. Fowler, and V. Goosey-Tolfrey1, “Effects of 4-weeks of asynchronous hand-rim wheelchair practice on mechanical efficiency and timing,” *Disabi. Rehabil.*, vol. 0, pp. 1–10, 2010.

[21] V. L. Goosey-Tolfrey, M. West, J. P. Lenton, and K. Tolfrey, “Influence of varied tempo music on wheelchair mechanical efficiency following 3-week practice,” *Int. J. Sports Med.*, vol. 32, pp. 126–31, Feb. 2011.

[22] W. X. Yao, A. Cordova, W. De Sola, C. Hart, and A. F. Yan, “The effect of variable practice on wheelchair propulsive efficiency and propulsive timing,” *Eur. J. Phys. Rehabil. Med.*, vol. 48, no. 2, pp. 209–216.

[23] W. X. W. Yao, W. W. DeSola, and Z. C. Z. Bi, “Variable practice versus constant practice in the acquisition of wheelchair propulsive speeds,” *Percept. Mot. Skills*, vol. 109, no. 1, pp. 133–139, 2009.

[24] S. de Groot, A. J. Dallmeijer, F. W. van Asbeck, M. W. Post, J. B. Bussmann, and L. van der Woude, “Mechanical efficiency and wheelchair performance during and after spinal cord injury rehabilitation,” *Int. J. Sports Med.*, vol. 28, pp. 880–6, Oct. 2007.

[25] S. de Groot, H. E. Veeger, A. P. Hollander, and L. H. van der Woude, “Adaptations in physiology and propulsion techniques during the initial phase of learning manual wheelchair propulsion,” *Am. J. Phys. Med. Rehabil.*, vol. 82, pp. 504–10, Jul. 2003.

[26] S. de Groot, H. E. Veeger, A. P. Hollander, and L. H. van der Woude, “Short-term adaptations in co-ordination during the initial phase of learning manual wheelchair propulsion,” *J. Electromyogr. Kinesiol.*, vol. 13, pp. 217–28, Jun. 2003.

[27] R. Vegter, C. Lamoth, S. de Groot, D. Veeger, and L. van der Woude, “Variability in bimanual wheelchair propulsion: consistency of two instrumented wheels during handrim wheelchair propulsion on a motor driven treadmill,” *J. Neuroeng. Rehabil.*, vol. 10, pp. 9–9, 2013.

[28] R. Withagen and M. v. Wermeskerken, “Individual differences in learning to perceive length by dynamic touch: Evidence for variation in perceptual learning capacities,” *Attent., Percept. Psychophys.*, vol. 71, pp. 64–75, Jan. 2009.

[29] V. Kostrubiec, P. -G. Zanone, A. Fuchs, and J. A. S. Kelso, “Beyond the blank slate: routes to learning new coordination patterns depend on the intrinsic dynamics of the learneróexperimental evidence and theoretical model,” *Front. Human Neurosci.*, vol. 6, 2012.

[30] A. C. King, R. Ranganathan, and K. M. Newell, “Individual differences in the exploration of a redundant space-time motor task,” *Neurosci. Lett.*, vol. 529, pp. 144–149, 2012.

[31] S. de Groot, H. E. Veeger, A. P. Hollander, and L. H. van der Woude, “Consequence of feedback-based learning of an effective hand rim wheelchair force production on mechanical efficiency,” *Clin. Biomech. (Bristol, Avon)*, vol. 17, pp. 219–26, Mar. 2002.

[32] D. Veeger, L. H. van der Woude, and R. H. Rozendal, “The effect of rear wheel camber in manual wheelchair propulsion,” *J. Rehabil. Res. Develop.*, vol. 26, pp. 37–46, 1989.

[33] L. Garby and A. Astrup, “The relationship between the respiratory quotient and the energy equivalent of oxygen during simultaneous glucose and lipid oxidation and lipogenesis,” *Acta Physiol. Scand.*, vol. 129, pp. 443–4, Mar. 1987.

[34] P. Sedgwick, “Multiple significance tests: the Bonferroni correction,” *BMJ*, vol. 344, 2012.

[35] J. Cohen, *Statistical Power Analysis for the Behavioral Sciences*, 2nd ed. Hillsdale, NJ: Routledge, 1988.

[36] J. Rasbash, C. Charlton, W. Browne, M. Healy, and B. Cameron, MLwiN Ver. 2.1 Center Multilevel Modell., Univ. Bristol, Bristol, U.K., 2009.

[37] G. J. van Ingen Schenau, “Cycle power: a predictive model,” *Endeavour*, vol. 12, pp. 44–7, 1988.

[38] M. L. Boninger, R. A. Cooper, M. A. Baldwin, S. D. Shimada, and A. Koontz, “Wheelchair pushrim kinetics: Body weight and median nerve function,” *Arch. Phys. Med. Rehabil.*, vol. 80, pp. 910–5, Aug. 1999.

[39] M. L. Boninger, A. L. Souza, R. A. Cooper, S. G. Fitzgerald, A. M. Koontz, and B. T. Fay, “Propulsion patterns and pushrim biomechanics in manual wheelchair propulsion,” *Arch. Phys. Med. Rehabil.*, vol. 83, pp. 718–723, 2002.

[40] K. M. Newell, Y. T. Liu, and G. Mayer-Kress, “Time scales in motor learning and development,” *Psychol. Rev.*, vol. 108, pp. 57–82, Jan. 2001.

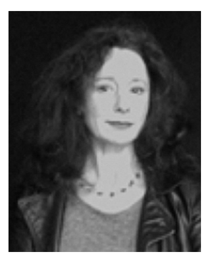
[41] S. de Groot, A. J. Dallmeijer, O. J. Kilkens, F. W. van Asbeck, A. V. Nene, E. L. Angenot, M. W. Post, and L. H. van der Woude, “Course of gross mechanical efficiency in handrim wheelchair propulsion during rehabilitation of people with spinal cord injury: A prospective cohort study,” *Arch. Phys. Med. Rehabil.*, vol. 86, pp. 1452–60, Jul. 2005.

Riemer J. K. Vegter is currently working toward the Ph.D. degree at the Center for Human Movement Science, University Medical Center Groningen, University of Groningen, Groningen, The Netherlands. Since 2009, his Ph.D. degree research is on motor learning processes underlying manual wheelchair skill acquisition, applying a combination of biomechanics, physiology and coordination dynamics. In this project the effects of practice on mechanical efficiency, mechanical loading of the upper extremities and the underlying changes in coordination are evaluated.

He is a Lecturer at the Center for Human Movement Science, University Medical Center Groningen, University of Groningen, Groningen, The Netherlands. From 2007 to 2009, he was a Junior Scientist on the biomechanical modeling of 4-bar prosthetic knee joints.

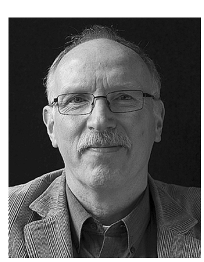
Sonja de Groot received the Ph.D. degree for the thesis “Manual wheelchair propulsion: biophysical aspects of learning,” from Vrije Universiteit Amsterdam, in 2003.

She is a Senior Researcher at Rehabilitation Center Reade, Amsterdam, The Netherlands, and Assistant Professor at the Center of Human Movement Sciences, University Medical Center Groningen, University of Groningen, Groningen, The Netherlands. After receiving the Ph.D. degree, she started as the coordinator of the multi-center research program “Restoration of mobility in SCI rehabilitation” and more recently as the coordinator of the subsequent multi-center research program “Active LifestyLe Rehabilitation Interventions in persons with a chronic Spinal Cord injury (ALLRISC)”.



Claudine J. Lamoth is an Assistant Professor and Principal Investigator at the Center of Human Movement Sciences, University Medical Center Groningen, Groningen, The Netherlands. Her research interest is in the area of motor control of learning, ageing and movement disorders, using concepts and tools from dynamical systems theory. This theoretical approach explicates variability as an inherent property of human movement and, in doing so; it provides an expedient window into the coordination of system components as well as its stable and adaptive features. She combines knowledge of motor control with innovative sensor technologies and data analysis to develop objective instruments for diagnosis and interventions.

Dirkjan Hej Veeger holds a position at the Department of Human Movement Sciences, Vrije Universiteit Amsterdam and Faculty of Mechanical Engineering, Section Biomedical Engineering, Delft University of Technology, Delft, The Netherlands. His main research interest lies in the field of musculoskeletal mechanics, and especially the upper extremity. Most profound research subject is the relationship between structure and function, which has been applied to wheelchair propulsion, the effect of surgical interventions such as tendon transfers on muscle function and ADL, but also to pitching in baseball.



Lucas van der Woude is Professor in “Human Movement, Rehabilitation and Functional Recovery at the Center for Human Movement Sciences” of the University Medical Center, University of Groningen, Groningen, The Netherlands, since January 1, 2009. He is program leader for Rehabilitation at the Center for Human Movement Sciences, and of ALLRISC and the SCIONN network, both focused on mobility restoration in persons with a spinal cord injury. Other long year interests are among others on wheeled mobility and its ergonomics optimization in both rehabilitation and adapted sports.